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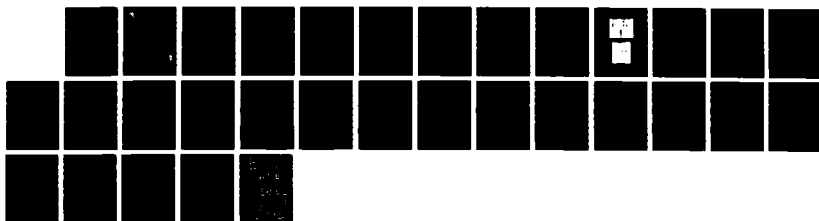
IN-HOUSE CAPACITOR TECHNOLOGY PROGRAM(U) AIR FORCE
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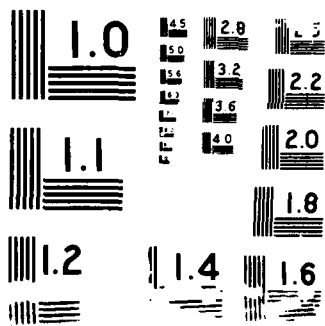
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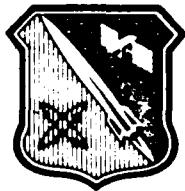
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AFAL-TR-88-002

AD:

Final Report
for the period
July 1977 to
February 1987

In-House Capacitor Technology Program

AD-A194 804

February 1988

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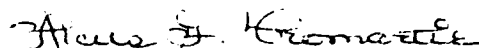
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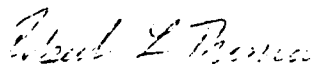
FOREWORD

This is the final report on the In-House Capacitor Technology Program for the Air Force Astronautics Laboratory (AFAL), Edwards Air Force Base, CA. The period of the report is July 1977 to February 1987. AFAL Project Manager was Alcus G. Cromartie.

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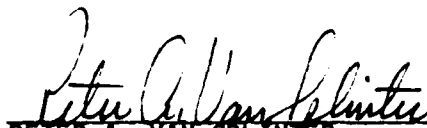


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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release, distribution is unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFAL-TR-88-002			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Air Force Astronautics Laboratory		6b. OFFICE SYMBOL (If applicable) TOAA	7a. NAME OF MONITORING ORGANIZATION		
6c. ADDRESS (City, State, and ZIP Code) Edwards AFB CA 93523-5000			7b. ADDRESS (City, State, and ZIP Code)		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
PROGRAM ELEMENT NO. 62302F		PROJECT NO. 3058	TASK NO. 12	WORK UNIT ACCESSION NO. SR	
11. TITLE (Include Security Classification) In-House Capacitor Technology Program (U)					
12. PERSONAL AUTHOR(S) Cote, Denis, Hausauer, Rudolph J., and Cromartie, Alcus G.					
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM 77/7 TO 87/2		14. DATE OF REPORT (Year, Month, Day) 88/2	
15. PAGE COUNT 31					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD 21	GROUP 03	SUB-GROUP	Energy, Density, K-Film, Polymer, Capacitor, TCP, DAP, MIPB, Silicone, Impregnant.		
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>This report presents the results of a technology program directed towards the development of a long-life high energy density capacitor for applications in space.</p> <p>The desired high energy density of the capacitors manufactured was 40 joules/pound. Life curve data was taken in order to validate the total number of capacitor discharges while operating at a rated voltage of 2.5Kv.</p> <p>The capacitors tested were paper free and were composed primarily of K-film (polyvinylidene fluoride), aluminum foil and an impregnant material. Of the several candidate impregnant materials (TCP, DAP, MIPB, and Silicone Oil), the silicone oil impregnant proved to be most successful for test purposes.</p> <p>Subsequently, various tests were conducted on the high energy density capacitors under various temperatures and vacuum conditions.</p>					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL Alcus G. Cromartie			22b. TELEPHONE (Include Area Code) (805) 275-5238		22c. OFFICE SYMBOL TOAA

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
GENERAL	
CAPACITOR DEVELOPMENT	1
SYSTEM OPERATION	3
PROBLEMS AND FINDINGS	5
TEST PERFORMANCE	
SYSTEM NO. 1	7
SYSTEM NO. 2	9
PROCEDURE	
FACILITY/SYSTEM (CONTROL AND OPERATION)	10
TEST RESULTS	12
CONCLUSIONS	14
BIBLIOGRAPHY	17
APPENDIX	19

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LIST OF FIGURES

<u>FIGURE</u>	<u>CAPTION</u>	<u>PAGE</u>
1	High Energy Density Capacitor	2
2	Diagram of Capacitor Test System No. 1	3
3	Capacitor Test Setup Equipment	4
4	Capacitor Test Setup Equipment	4
5	Temperature vs Pulse	5
6	Capacitance vs Pulse	5
7	Diagram of Capacitor Test System No. 2	6
8	Maxwell Capacitor Internal Temperature Measurement System	7
9a	Start Up Sequence Flow Chart	8
9b	Capacitor Pulsing Flow Diagrams	8
9c	Capacitor Diagnostics Flow Chart	9
10	AFAL Capacitor Mechanical Schematic	10

INTRODUCTION

The Air Force Astronautics Laboratory (AFAL) has an on-going development program for a solid teflon pulsed plasma thruster for deep space applications. The high specific-impulse performance and inherent simplicity of the pulsed plasma thruster makes it a prime candidate for deep space applications. The thruster being developed is expected to generate approximately 4.4 milli-Newtons (1.0 milli-pounds) of thrust. The intended thruster applications dictate a 7 to 10 year life span and will undergo approximately 15 million pulses.

The Air Force presently uses small pulsed plasma thrusters for satellite station keeping. These pulsed plasma thrusters use high energy density capacitors to provide the propulsion energy necessary for thrust.

The capacitor technology project was originally conceived because available high energy density capacitors were not adequate for the larger pulse plasma thruster program. Since the heart of the pulsed plasma thruster is the high energy density capacitor system, it became imperative to develop a reliable capacitor to meet this requirement.

The prototype thruster under development uses four high energy density capacitors as an energy storage medium between pulses. These capacitors are connected in parallel to provide a total capacitance of 240 microfarads and store approximately 650 joules of energy for thruster discharge.

The initial project objective was to evaluate the life, reliability, and performance of high energy capacitors for use on the one millipound solid teflon pulsed plasma thruster during a 7 to 10 year, 15 million pulse, North-South station keeping mission.

Capacitors representing the current state of high energy density technology were to be "tested-to-failure" in both vacuum and air environments to generate life cycle curve data.

GENERAL

CAPACITOR DEVELOPMENT

As a result of the development of the millipound prototype solid Teflon pulsed plasma thruster, the Fairchild Republic Company introduced a capacitor technology spinoff that required further study into producing a high energy density capacitor for the millipound thruster program.

However, producing such a pulsed plasma capacitor posed two unique design problems. It required that a manufacturer create a capacitor with a high energy density while ensuring that the capacitor had an extremely long life. A high energy density capacitor would provide a substantial weight saving in the thruster, and would also increase the chances for successful missions through the use of long-life capacitors.

The energy requirements for long duration thruster operations dictated that a 240 microfarad capacitor rated at 650 joules be developed. A single 240 microfarad capacitor was originally constructed. Shortly thereafter, however, a decision was made to manufacture four separate capacitors, each

rated at 40 joules per pound. This implied that each thruster capacitor would weigh approximately 4.1 pounds.

Even though the energy requirement of a 40 joule per pound capacitor is not great, it is known that capacitors with high energy levels have short lives. It is known, for example, that certain utility companies have used 300 joules per pound capacitors with life expectancies 100 times greater than those required by this project.

The underlying design factors of the utility companies' capacitors were their overall large size and their low effective energy density versus long life characteristics. Therefore, some type of trade-off had to be made in this AFAL capacitor study. There had to be a trade-off between a capacitor's long life and its high energy density in order to have a successful thruster mission. Thus an AFAL search began for high caliber capacitor manufacturers who could design, develop, and manufacture a capacitor capable of operating for 15 million pulses (with high energy densities).

Several manufacturers throughout the life of the project participated in creating various types of high energy density capacitors for test and evaluation. Several types of dielectric materials, in particular, polyvinylidene fluoride (K-film), tricresyl phosphate (TCP), Diallyl Phthalate-Monomer (DAP), Monoisopropyl Biphenyl (MIPB), and Silicone oil were chosen as prospective candidates for the pulsed plasma thruster. (For further information refer to AFRPL-TR-80-035).

After much research, testing, and evaluation K-film was chosen as the dielectric to be used because of its slightly longer life, better physical appearance, and its higher dielectric constant. Figure 1 shows a typical high energy density capacitor.

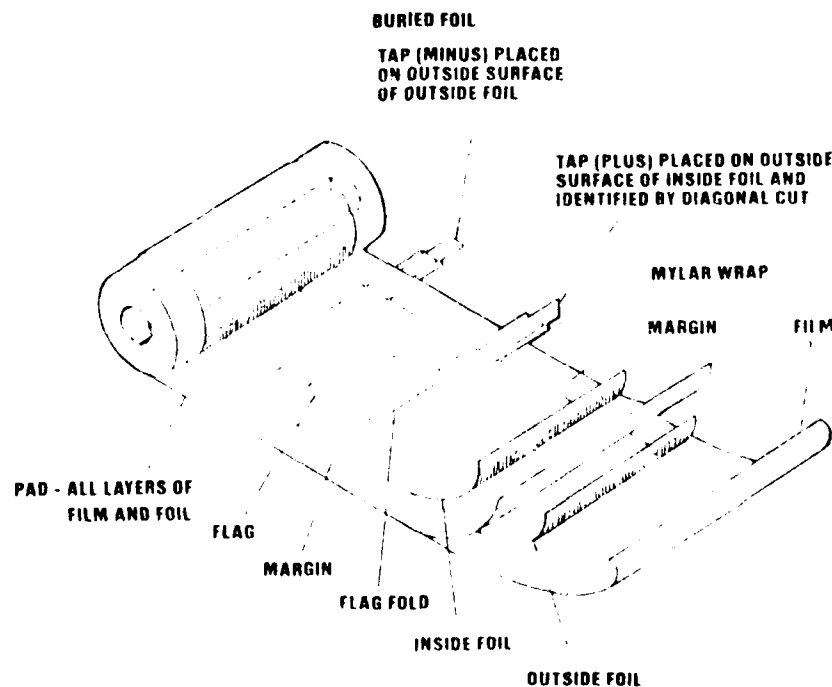


Figure 1. High Energy Density Capacitor.

Thirty-three capacitors were tested in this project, and 32 capacitors failed during testing, with one capacitor selected to be placed in storage.

SYSTEM OPERATION

The AFAL designed and developed a microcomputer system to control the capacitor's charge and discharge cycle, acquire pertinent data regarding the capacitor's health, make decisions for future actions based on the acquired data, and monitor the test experiment's facility status to ensure safe operation. Figure 2 shows the logic block diagram for the automated test setup for System 1.

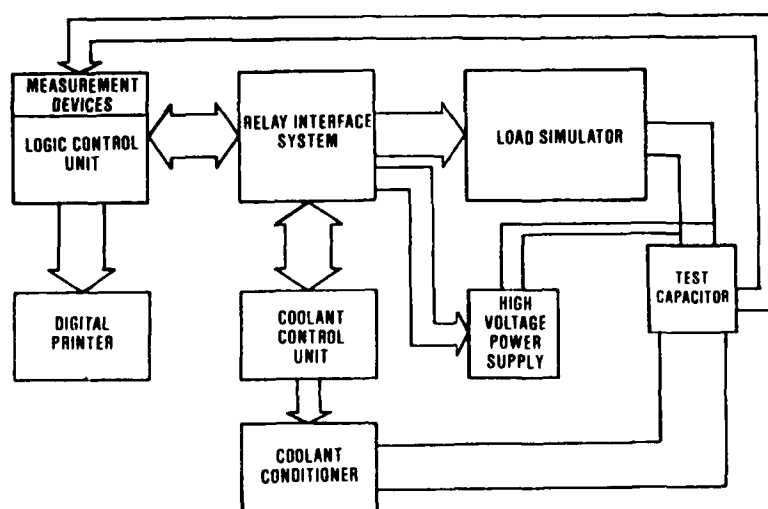


Figure 2. Diagram of Capacitor Test System No. 1.

The pulse repetition rate for the microcomputer system ranged between 0.111 and 0.4 pulses per second. Capacitor charging was accomplished by high voltage laboratory supplies. Once charged, the capacitor discharged through an ignitron tube and load simulator which approximated the actual pulsed plasma thruster's electrical characteristics. Figures 3 and 4 show the capacitor test setup equipment.

Temperature, voltage, leakage current, capacitance and dissipation factor data were acquired by the microcomputer and certain control decisions were made based on the values of this data. Data acquired from the capacitor under test included capacitor temperature, heat sink temperature, capacitor voltage, and capacitor pulse number. Figures 5 and 6 show typical changes in temperature and capacitance. The temperature sensors were two thermocouples which had been welded or epoxied onto the "ground-reference" side of the capacitor and its heat sink. The capacitor's voltage was taken from a very

high resistance precision voltage divider placed across the test capacitor. The capacitor's pulse number was generated by an internal counter maintained in the microcomputer by its software. After the first test series, the microcomputer system was upgraded. Figure 7 shows the new logic block diagram for System 2.



Figure 3. Capacitor Test Setup Equipment.



Figure 4. Capacitor Test Setup Equipment.

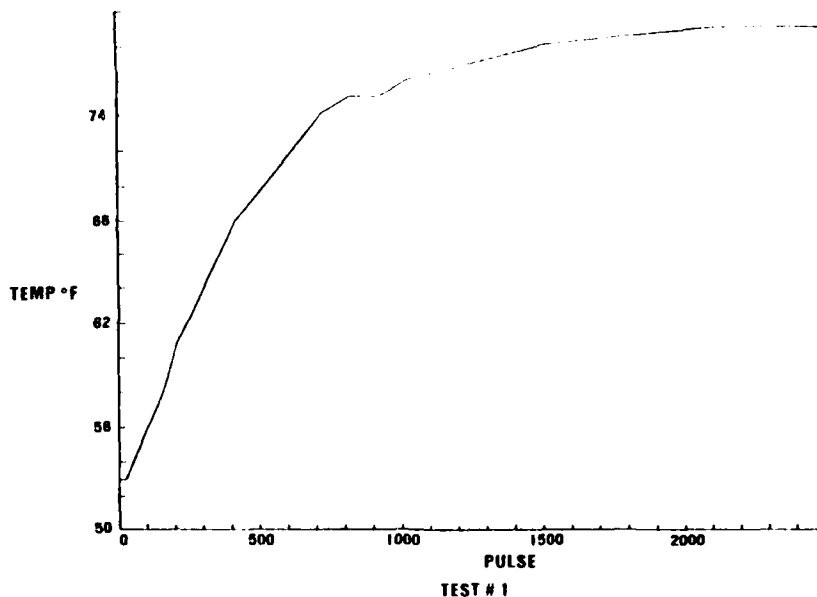


Figure 5. Temperature vs Pulse.

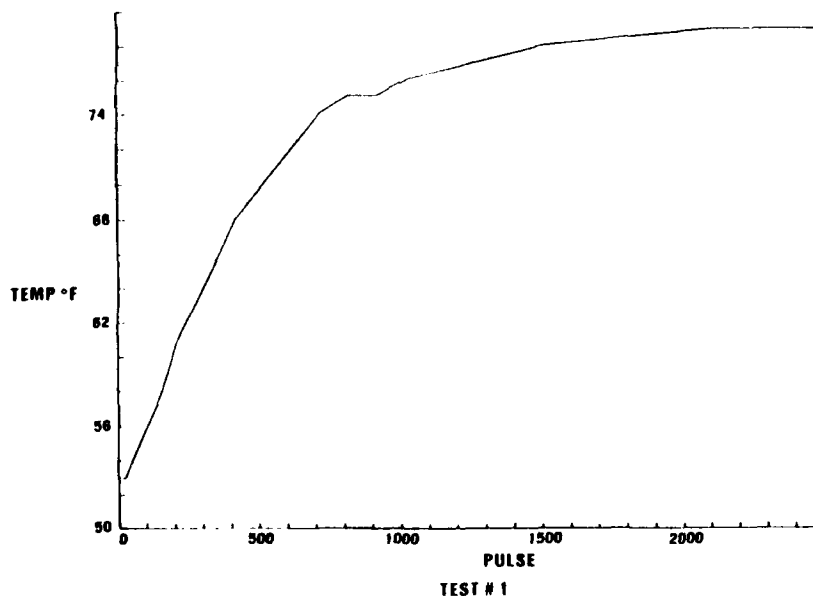


Figure 6. Capacitance vs Pulse.

PROBLEMS AND FINDINGS

The project provided confirmation of possible problems with the newly designed K-film/silicone oil high energy density capacitors (Fig. 1). Early in the project, a capacitor failure was experienced on a laboratory-pulsed plasma thruster at Fairchild Republic during an AFAL program. The failure

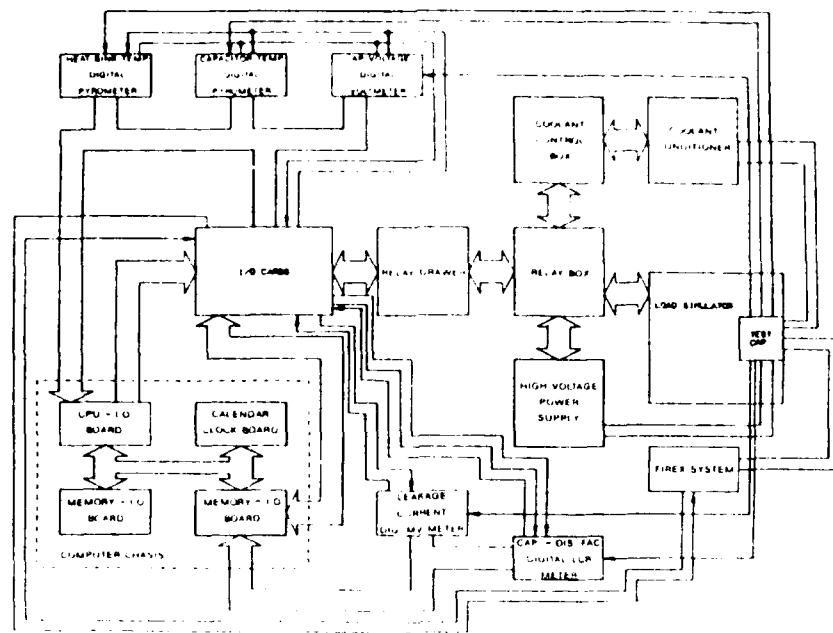


Figure 7. Diagram of Technology Test System No. 2.

occurred after about 52,000 capacitor pulses; yet the capacitor's design life was rated for 10 to 15 million pulses. This failure indicated that a potential capacitor design problem existed. Soon after, a second K-film/silicone oil capacitor was placed into test at the AFAL using an automated test system and simulated thruster load. Again, another failure was experienced on this second K-film capacitor after 84,679 pulses, seeming to confirm Fairchild's failure point. A third capacitor was placed into test to either confirm or deny the previous results; it too failed at 350,813 pulses.

The test results of the third capacitor confirmed that the capacitor which yielded the longest life was distinctly different from any of the other capacitors tested. The difference was that part way into its life cycle, the longer life capacitor developed an internal oil leak; yet this leak did not hinder the testing of the capacitor. The leak allowed the capacitor's internal temperature and pressure to be dissipated more readily, thereby increasing its life span.

As a result of this test, a recommendation was made to test several theories by creating three very special capacitors for use in a series of experiments. The first capacitor would have a relief valve mounted inside which would allow the internal pressure of the capacitor to be relieved while observing the effects of the experiment. A second capacitor would have several sets of thermocouples mounted to its plates at various positions within the capacitor to determine the actual temperature of these plates and determine whether these temperatures were hot enough to cause "blow-through"

in the mylar; and a third capacitor, instead of having a normal bellows (Fig. 8), would have a cooling coil mounted in the center of the capacitor which could be plumbed into the test facility's cooling system. The cooling rate was approximately 1.2 gallons per minute. This setup would allow for the removal of heat from the center of the capacitor, and determine whether or not removing the heat from the inside of the capacitor could increase the capacitor's life expectancy.

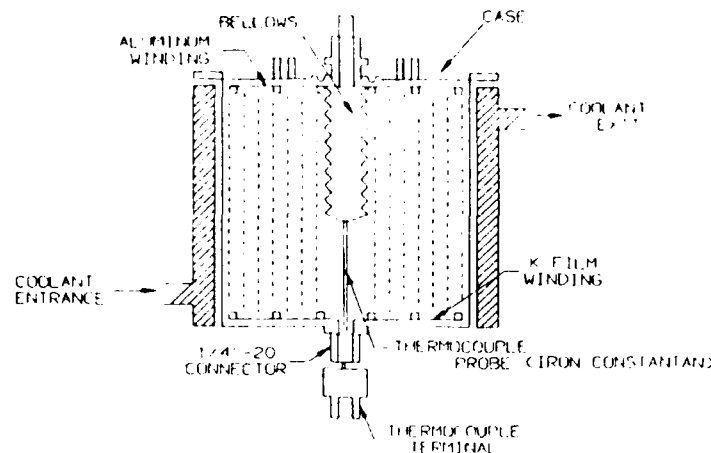


Figure 8. Maxwell Capacitor Internal Temperature Measurement System.

However, during the course of this project several funding cuts occurred. Due to these cuts, only a small number of autopsies were performed on these capacitors. Reports from external autopsies conducted and from autopsies conducted at the AFAL confirmed that the most common failure mode of all of the capacitors tested was caused by a short between the plates.

TEST PERFORMANCE

SYSTEM NO. 1

The control, data acquisition, and safety monitoring system for the first capacitor test system was designed and fabricated at the AFAL using wirewrapped integrated circuit logic (Fig. 2). The data acquired by the system included capacitor temperature (Fig. 5), capacitor heat sink temperature, capacitor voltage, and pulse number. Engineering units digital data was generated by parallel digital panel meters. This parallel digital data was input to an AFAL designed and built data logger system (Fig. 9a). The capacitor's temperature data was limit checked in order to verify that its temperature was less than 104°F. Temperatures greater than that resulted in an automatic system shutdown.

The pre-discharge capacitor voltage was also limit checked. Deviation from preset limits also initiated an automatic shutdown (Fig. 9b). The capacitor's voltage was again checked after discharge to verify that it was less than 20 volts, which indicated that the capacitor had successfully discharged.

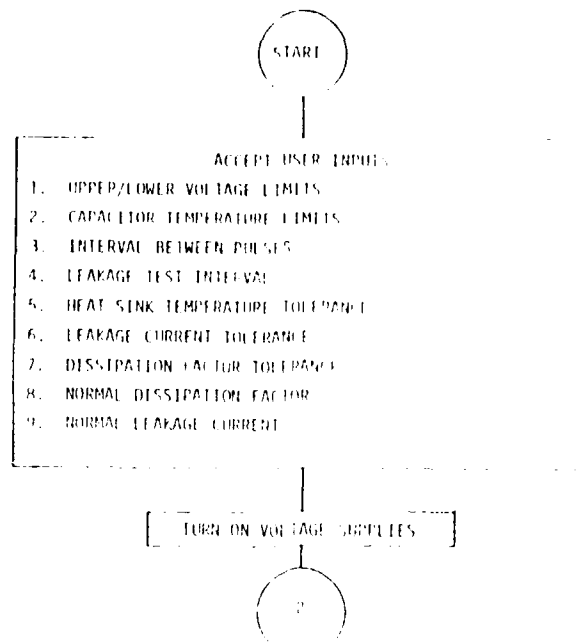


Figure 9a. Start Up Flow Chart.

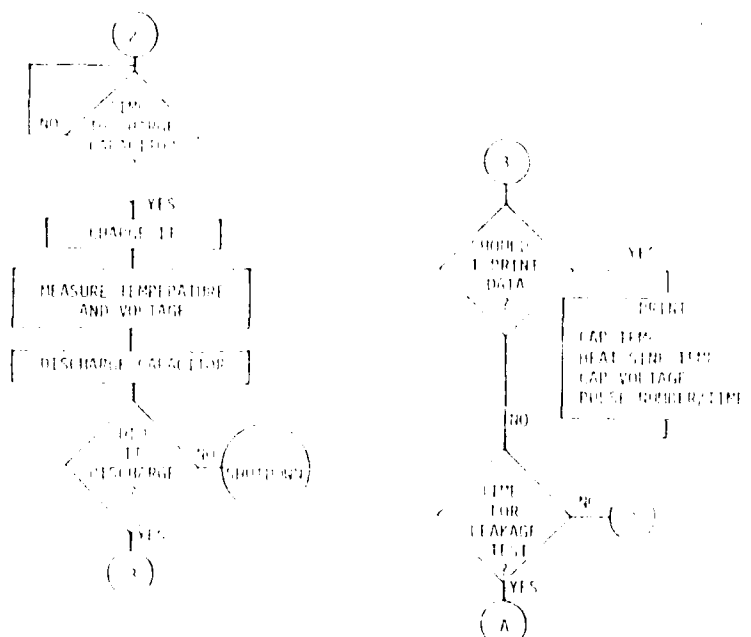


Figure 9b. Capacitor Pulsing Flow Diagrams.

In order to acquire capacitance, dissipation factor, and leakage current data on the test capacitor, the capacitor test had to be terminated. The capacitor was then isolated and measurements were made manually with an impedance bridge. A front panel control on the monitoring system allowed the operator to select the data print interval (in the range of 1 to 100 pulses per second) (Fig. 9c).

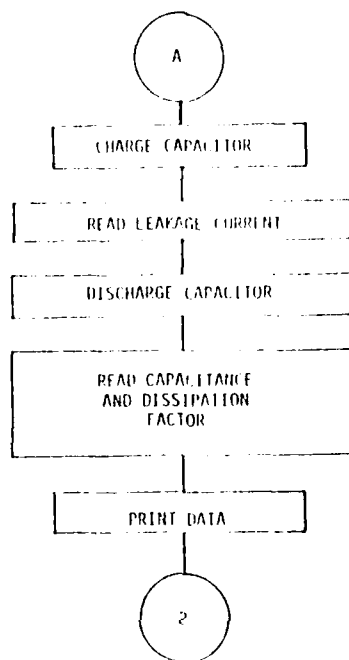


Figure 9c. Capacitor Diagnostics Flow Chart.

The capacitor's test system (a hard-wire design) was capable of monitoring all of the safety parameters sufficiently in order to permit unmanned operations, but did not lend itself to change and was therefore no longer cost effective.

SYSTEM NO. 2

The AFAL chose to include a microcomputer as the central controlling element for the second capacitor evaluation system (Fig. 7). Inclusion of an INTEL-based microcomputer as the central controlling element provided decision-making capabilities which did not exist with the initial hard wired system.

A microcomputer system was chosen primarily because it vastly reduced the manhours required for system fabrication. The microprocessor chosen for the capacitor evaluation system was an INTEL 8080A eight bit processor. The 8080A was implemented as a component part of the INTEL's single board computer series. Included on the operator's console was a Texas Instruments Silent 743 thermal printing terminal which made faster printing possible. This terminal served as both the operator's console and data printer.

During the course of operation, the computer system was modified to include more memory capability and gave the capacitor test system more data input capability, if needed. The INTEL single board computer, Model No. SBC 80/20-4 contained the 8080A microprocessor with its 4K bytes of random access memory (RAM), 8K bytes of read only memory (ROM), serial interface circuitry terminal, and 48 input/output bits. Two SBC-116 memory and input/output boards were also provided; one of which was originally included with the other added later to upgrade the system. Each of these boards provided 16K bytes of RAM, 8K bytes of ROM, and 48 input/output bits. A real time clock board was also added to save writing a software routine for the microcomputer.

PROCEDURE

FACILITY/SYSTEM (CONTROL AND OPERATION)

The entire facility control system was implemented with a manual override capability. All control functions could be executed manually from the operator's panel or the operator could relinquish control to the microcomputer. The controls provided for by the switch panel were sufficient for the operator to step through an entire charging, data taking, and discharge sequence. Manual control was also provided for facility safety items as well.

A forced coolant system was provided for the capacitors in order to enable them to be pulsed at a faster rate without overheating (Fig. 10). This coolant system was activated by the microcomputer control system. When an acceptable flow rate was achieved, a flow switch was energized and signaled the microcomputer that an acceptable coolant flow rate existed. The loss of the coolant flow signal would initiate a system shutdown. Additionally, fire detection and extinguishing circuitry was hardware controlled. If the fire extinguishing system was energized by the console, detection of a fire by a sensor automatically activated the extinguisher system. Once activated, the fire sensing signal is sent to the microcomputer so that the facility could be secured.

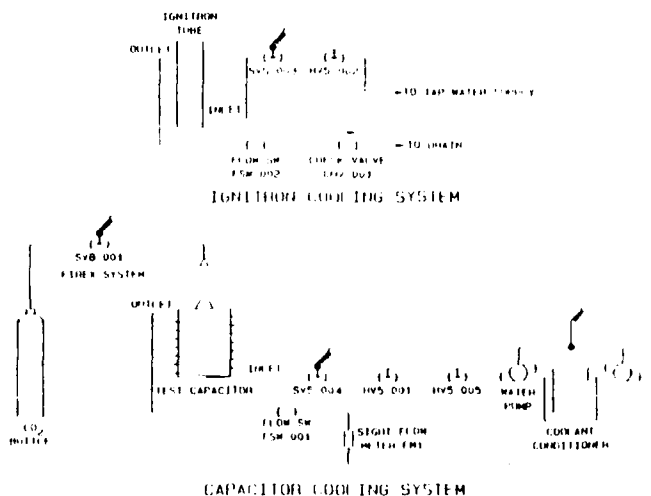


Figure 10. AFAL Capacitor Mechanical Schematic.

The pulsed plasma thruster simulator for the computerized test system (Fig. 2) is essentially the same as the one employed on the original capacitor test system built by the AFAL (Fig. 1). A mechanical repackaging was accomplished to facilitate troubleshooting and component replacement. Electrically, however, the load simulator for the second capacitor system is identical to the first system.

Large discharge currents flow through the system during the discharge cycle, so it was decided to disconnect all instrumentation during discharge. These large currents flowing through ground caused sizeable "common mode" voltages to be applied to the instruments. Since the instrument sensors were referenced near ground, these common mode voltages were not considered to be destructive. Therefore, the instrument sensors were not subjected to the electrical stress of these large discharge currents. Actually, the sensors were disconnected at all times until the microcomputer was ready to acquire a data reading. The sensors were then connected to the capacitor through high voltage relays.

The most standard technique of acquiring analog data through a microcomputer was to include a multiplexer and an analog-to-digital converter in the system. Several buss compatible printed circuit boards were available from the INTEL-multibus system that could perform these sampling and digitizing functions. All of these boards required some application software to acquire the data, convert the data to a digital value and then scale it to meaningful engineering units.

In the past, the capacitor data was sampled each 1 to 100 pulses where the pulse/rate was from 1 to 10 seconds. Since this data sampling rate is very slow, it was decided to acquire the data using digital panel meters. Using digital panel meters greatly simplified the computer software needed to run the system. The data sensor outputs were connected to the inputs of the digital panel meters. Upon command from the microcomputer, the sensors were connected to the test capacitor and commanded to acquire and digitize a data sample. The microcomputer would then convert the sample to an engineering units value, output that value on parallel digital lines, and hold the value until instructed to acquire a new data sample.

The microcomputer monitors "data ready" commands from the digital panel meters. When all of the meters had made their engineering units data available the computer would then read that data into memory. The temperature and voltage readings are actually read twice during each pulse cycle, just prior to discharging the capacitor and immediately following the discharge.

The predischage capacitor voltage is limit-checked by the microcomputer against a nominal value and an allowable duration as input by the operator. The capacitor's voltage is sampled again after the capacitor has been discharged. A nominal voltage reading after successful discharge generally is on the order of 20 volts. The capacitor temperature acquired before discharge is used to determine an over-temperature condition. The maximum allowable capacitor temperature is an operator controlled input.

Inclusion of a microcomputer in the capacitor's evaluation system has paid dividends. The initial test system acquired and printed data at specific intervals as determined by the operator. The microcomputer in the second system had decision making capabilities. A simple data compression algorithm was employed to limit the amount of data printed. A subsequent version of the software program changed the data from raw engineering units to high, low, average, and standard deviation values of each parameter.

On the earlier AFAL-developed test system, the capacitor test system had to be shut down periodically and the capacitor isolated so its capacitance, dissipation, and leakage factors could be measured with an impedance bridge. This was a disruptive and time-consuming task. Additionally, since the test system could be operated unmanned, the measurement intervals were arranged for periods when the facility was manned. These unmanned periods sometimes resulted in large intervals of time when data was not recorded.

The computerized second capacitor test system automatically acquired capacitance, dissipation factor, and leakage current data. Included in the system was a Hewlett-Packard digital LCR meter (Model 4261A). This meter was provided with parallel digital outputs for both capacitance and dissipation factor measurements.

At intervals specified by the operator, the second capacitor test system dissipated all of the energy stored in the test capacitor. This system could also isolate the test capacitor from the other circuitry while connecting the LCR meter to the test capacitor, or while measuring the capacitor's capacitance and dissipation factors. The data acquired is then converted into parallel digital engineering units and made available to the microcomputer for processing. The computer would then compare the engineering unit data with data stored within its memory. Depending on the "delta parameters" which had been input by the operator, the sampling process could be adjusted.

TEST RESULTS

Project test results were acquired in AFAL's Satellite Propulsion Complex. This area was chosen for capacitor testing because of its high vacuum chamber laboratory, and because the laboratory also had a bench test facility that could be used for air testing the capacitors.

Two load simulators with electrical discharge properties closely approximating those of the actual solid Teflon pulsed plasma thruster were fabricated inside the vacuum chamber to acquire data. One of the load simulators was used for air testing the capacitors and the other was used for vacuum testing of the capacitors.

Fairchild Corporation, Maxwell Laboratories, and Sandia Laboratory provided specially designed K-film capacitors for this study. Of the 33 capacitors fabricated and tested, 10 K-film/paper/castor oil capacitors were built by Maxwell Laboratories using the Fairchild Republic specifications. Maxwell also built eight K-film/paper/castor oil capacitors as well as seven special K-film/paper/castor oil capacitors. Eight subscale special K-film capacitors were fabricated by Sandia Laboratory.

Temperature measurements were taken inside some of the capacitors, where it was noted that the temperature rose exponentially to about 80°F after approximately 2000 pulses (Fig. 5). It was also noted that the capacitance of those capacitors plotted rose slightly with temperature (Fig. 6). The temperature rise did not seem to be high enough to melt mylar, yet the mylar film failed near the center of each capacitor, in a failure mode best described as "blow-through." Table 1 shows some of the failure results from the Maxwell capacitors tested on System 1.

Table 1. Maxwell Laboratories Capacitor Failure Results

<u>Test #</u>	<u>Model #</u>	<u>Pulse Failure (Cycles)</u>	<u>Test Voltage (Volts)</u>
1	CT1-1	unk	unk
2	CT1-2	1436	2500
3	CT1-3	885	3750
4	CT1-4	8841	3500
5	CT1-5	8432	2500
6	CT1-6	602526	2500
7	CT1-7	7445	4000
8	CT1-8	524	3750
9	CT1-9	15586	3500
10	CT1-10	1869126*	2500
11	CT1-11	84679	2200
12	CT1-12	350813	2200
13	CT1-13	7000+	2200

*Developed leak at 964129 pulses, testing continued.

After these tests were completed, testing started on more Maxwell capacitors and some of the Sandia subscale capacitors using Test System 2. The major configuration change to the microcomputer was a change from hard-wire circuitry to printed circuit boards and new system software. A digital capacitance and dissipation factor meter was also added to System 2 (see Fig. 7).

Table 2 lists the results of the Maxwell and the Sandia subscale capacitor failures that occurred using System 2.

Table 2. Capacitor Failures Using System 2

<u>Test #</u>	<u>Model #</u>	<u>Pulse Failure (Cycles)</u>	<u>Test Voltage (Volts)</u>
14	CT2-1	72864	2200
15	CT202	15398	2200
16	CT2-3*	40475	2000
17	CT2-4	65695	2000
18	CT2-5	15925	2200
19	CT2-6	260438	2800

Table 2. Capacitor Failures Using System 2 (concluded)

<u>Test #</u>	<u>Model #</u>	<u>Pulse Failure (Cycles)</u>	<u>Test Voltage (Volts)</u>
20	CT2-7	963	3800
21	CT2-8A	1957	3800
22	CT2-8	260438	3200
23	CT2-9	1863046	2400
24	CT2-10	1658721	2400
25	CT2-11**	44812	2400
26	CT2-12	192672	2500
27	CT2-13	130615	2000
28	CT2-14	54698	3000
29	CT2-15	0	3000
30	CT2-16	unk	3800
31	CT2-17	192672	2500
32	CT2-18	27896	2500
33	CT2-19	379278	2500

* Also known as capacitor "Reject X"

** CT2-11 terminated at 44812 pulses, then stored.

CONCLUSIONS

The most common failure of the capacitors tested was a short between the plates. The short was usually attributed to what appears to be "blow-through" of the mylar sheet separating the two plates. The location of the "blow-through" was, in general, somewhere near the center of the capacitor.

Testing of K-film/paper/castor oil capacitors indicated they could be expected to complete approximately 180,000 discharges before failure at a rated voltage of 3.2 Kv. Autopsies of the failed capacitors revealed a high percentage of body failures normally associated with film quality, material, and manufacturing defects. Test results also indicated a fundamental problem existed in the K-film/silicone oil capacitor design. The average life of these type capacitors was found to be about 80,000 discharges at an average rated voltage of 2150 volts. Again, the pulse repetition rate varied between 0.2 and 0.4 pulses per second.

Test results for K-film/castor oil capacitors showed the average life of these type capacitors is approximately 500,000 discharges at an average rated voltage of 3000 volts. The average discharge pulses for the Sandia subscale capacitors was approximately 160,000 pulses at an average rated voltage of 2500 volts. Again, the pulse repetition rate varied between 0.2 and 0.4 pulses per second.

The fact that the third capacitor lasted longer than any other prompted the belief that the temperature and pressure buildup within the capacitors has a direct bearing on their life. Temperature measurements taken inside the capacitors confirmed that the capacitance rises only slightly and the internal temperature rise is not hot enough to melt the mylar, yet "blow-through" still occurred.

In summary, a critique of the data obtained from the capacitor tests clearly reflects the notion that high energy density capacitors must be considered to be a complex system in which the ultimate performance of the capacitor material depends on its virgin state, how the material was handled, and how it was processed into capacitors. The system's complexity is also a function of its test environment.

All of the test equipment involved in this project has been preserved for further studies. Any future use of this test equipment on other capacitor research projects will greatly enhance the probability of data repeatability and reliability, thus aiding in the analysis of the many inherent capacitor failure modes.

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APPENDIX

TABLE A-1. Capacitor Test Dates

Capacitor ID #	Test Date From	Test Date To
CT1-1	Unknown	Unknown
CT1-2	01-24-79	02-06-79
CT1-3	02-07-79	02-07-79
CT1-4	02-13-79	02-28-79
CT1-5	03-01-79	03-02-79
CT1-6	03-09-79	11-23-79
CT1-7	11-29-79	11-30-79
CT1-8	12-04-79	12-04-79
CT1-9	12-05-79	12-06-79
CT1-10	12-18-79	01-02-80
CT1-11	01-02-81	01-15-81
CT1-12	01-23-81	01-26-81
CT1-13	01-27-81	01-27-81
CT2-1	01-22-81	03-22-81
CT2-2	03-23-81	03-25-81
CT2-3	03-21-81	04-02-81
CT2-4	08-13-81	11-30-81
CT2-5	12-21-81	12-23-81
CT2-6	02-08-82	04-16-82
CT2-7	05-03-82	05-03-82
CT2-8	07-07-82	07-29-82
CT2-8A	05-05-82	05-05-82
CT2-9	08-06-82	01-09-83
CT2-10	05-06-83	11-04-83
CT2-11	02-08-84	02-14-84
CT2-12	03-29-84	06-19-84
CT2-13	04-06-84	04-16-84
CT2-14	04-17-84	04-19-84
CT2-15	05-01-84	05-01-84
CT2-16	05-31-84	05-31-84
CT2-17	Unknown	Unknown
CT2-18	06-28-84	08-02-84
CT2-19	08-03-84	08-11-84

Table A-2. Capacitor Serial Numbers.

Capacitor ID #	Capacitor S/N
CT1-1	Unknown
CT1-2	78109
CT1-3	78114
CT1-4	78120
CT1-5	78108
CT1-6	78115
CT1-7	7811?
CT1-8	Unknown
CT1-9	78121
CT1-10	78118
CT1-11	111098
CT1-12	111095
CT1-13	111104
CT2-1	34217
CT2-2	111101
CT2-3	1?????
CT2-4	111103
CT2-5	Unknown
CT2-6	140099
CT2-7	142529
CT2-8	140098
CT2-8A	140095
CT2-9	142537
CT2-10	142530
CT2-11	142528
CT2-12	SC230K160-007K3
CT2-13	SC230K160-008K3
CT2-14	SC230K160-010K3
CT2-15	SC230K160-011K3
CT2-16	SC230K160-010K3
CT2-17	SC230K160-007K3
CT2-18	SC230K160-012K3
CT2-19	SC230K160-008K3

Table A-3. Capacitor Manufacturer/Dielectric Material

Capacitor ID #	Manufacturer	Dielectric/Filler
CT1-1	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-2	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-3	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-4	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-5	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-6	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-7	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-8	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-9	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-10	Maxwell Laboratory (FR)*	K-film/paper/castor oil
CT1-11	Maxwell Laboratory (FR)*	K-film/silicone oil
CT1-12	Maxwell Laboratory (FR)*	K-film/silicone oil
CT1-13	Maxwell Laboratory (FR)*	K-film/silicone oil
CT2-1	Maxwell Laboratory	K-film/silicone oil
CT2-2	Maxwell Laboratory	K-film/silicone oil
CT2-3	Maxwell Laboratory	K-film/silicone oil
CT2-4	Maxwell Laboratory	K-film/silicone oil
CT2-5	Maxwell Laboratory	K-film/silicone oil
CT2-6	Maxwell Laboratory	K-film/paper/castor oil
CT2-7	Maxwell Laboratory	K-film/paper/castor oil
CT2-8	Maxwell Laboratory	K-film/paper/castor oil
CT2-8A	Maxwell Laboratory	K-film/paper/castor oil
CT2-9	Maxwell Laboratory	K-film/paper/castor oil
CT2-10	Maxwell Laboratory	K-film/paper/castor oil
CT2-11	Maxwell Laboratory	K-film/paper/castor oil
CT2-12	Sandia	K-film/perfluorocarbon
CT2-13	Sandia	K-film/perfluorocarbon
CT2-14	Sandia	K-film/perfluorocarbon
CT2-15	Sandia	K-film/perfluorocarbon
CT2-16	Sandia	K-film/perfluorocarbon
CT2-17	Sandia	K-film/perfluorocarbon
CT2-18	Sandia	K-film/perfluorocarbon
CT2-19	Sandia	K-film/perfluorocarbon

*Fairchild Republic

Table A-4. Capacitor Repetition Rate/Failure Mode

Capacitor ID #	Pulse Rep. Rate (pulses/sec)	Failure Mode
CT1-1	Unknown	Unknown
CT1-2	0.45454	Shorted
CT1-3	0.45454	Shorted
CT1-4	0.45454	Shorted
CT1-5	0.45454	Shorted
CT1-6	0.45454 to 0.2	Shorted
CT1-7	0.14285	Shorted
CT1-8	0.2	Shorted
CT1-9	0.2	Shorted
CT1-10	0.2	Shorted
CT1-11	0.16667	Shorted
CT1-12	0.16667	Shorted
CT1-13	D.C. life test	Shorted
CT2-1	0.5	Shorted
CT2-2	0.25	Shorted
CT2-3	0.25	Shorted
CT2-4	0.25	Shorted
CT2-5	0.25	Shorted
CT2-6	0.25	Shorted
CT2-7	0.16667	Shorted
CT2-8	0.16667	Shorted
CT2-8A	0.11111	Shorted
CT2-9	0.2	Shorted
CT2-10	0.2	Shorted
CT2-11	0.4	None, Stored
CT2-12	0.4	Shorted
CT2-13	0.4	Shorted
CT2-14	0.4	Shorted
CT2-15	0.4	Shorted
CT2-16	0.4	Shorted
CT2-17	0.4	Shorted
CT2-18	0.4	Shorted
CT2-19	0.4	Shorted

Table A-5. Capacitor Nominal Voltage/Current

Capacitor ID #	Nominal Voltage (volts)	Nominal Current (amps*)
CT1-1	Unk.	Unk.
CT1-2	2500	34915
CT1-3	3750	52373
CT1-4	3500	48881
CT1-5	3000	41898
CT1-6	2500	34915
CT1-7	4000	55865
CT1-8	3750	52373
CT1-9	3500	48881
CT1-10	2500	34915
CT1-11	2200	30725
CT1-12	2200	30725
CT1-13	2500	N/A
CT2-1	2200	30131
CT2-2	2200	30131
CT2-3	2000	27392
CT2-4	2200	30131
CT2-5	2200	30131
CT2-6	2800	31429
CT2-7	3800	54286
CT2-8	3200	45714
CT2-8A	3800	54286
CT2-9	2400	34286
CT2-10	2400	34286
CT2-11	2400	34286
CT2-12	2500	4902
CT2-13	2000	3922
CT2-14	3000	5882
CT2-15	4000	7843
CT2-16	3800	7451
CT2-17	2500	4902
CT2-18	2500	4902
CT2-19	2500	4902

*Instantaneous current as measured across 0.0001256 ohms.

Table A-6. Capacitor/Heat Sink Temperatures

Capacitor ID #	Nominal Capacitor Temperature (°C)	Nominal Heat Sink Temperature (°C)
CT1-1	Unk.	Unk.
CT1-2	Unk.	Unk.
CT1-3	33	28
CT1-4	31	25
CT1-5	27	22
CT1-6	31	25
CT1-7	27	21
CT1-8	20	18
CT1-9	25	17
CT1-10	21	15
CT1-11	17	9
CT1-12	18	9
CT1-13	N/A	N/A
CT2-1	33	15
CT2-2	25	13
CT2-3	35	14
CT2-4	29	18
CT2-5	22	11
CT2-6	25	11
CT2-7	33	18
CT2-8	27	11
CT2-8A	30	10
CT2-9	21	13
CT2-10	26	17
CT2-11	23	27
CT2-12	20	20
CT2-13	20	23
CT2-14	22	22
CT2-15	21	21
CT2-16	27	27
CT2-17	Unk.	Unk.
CT2-18	20	23
CT2-19	21	21

Table A-7. Capacitance/Simulator/System Number.

Capacitor	Capacitance (ufd)	Simulator System #
CT1-1	Unk.	Unk.
CT1-2	61.4	1
CT1-3	60.8	1
CT1-4	61.0	1
CT1-5	61.1	1
CT1-6	61.0	1
CT1-7	60.5	1
CT1-8	60.0	1
CT1-9	60.0	1
CT1-10	Unk.	1
CT1-11	75.8	1
CT1-12	75.0	1
CT1-13	75.0	1
CT2-1	Unk.	2
CT2-2	Unk.	2
CT2-3	Unk.	2
CT2-4	Unk.	2
CT2-5	Unk.	2
CT2-6	Unk.	2
CT2-7	Unk.	2
CT2-8	Unk.	2
CT2-8A	Unk.	2
CT2-9	Unk.	2
CT2-10	70.0	2
CT2-11	70.0	2
CT2-12	70.0	2
CT2-13	4.7	2
CT2-14	4.7	2
CT2-15	Unk.	2
CT2-16	75.0	2
CT2-17	Unk.	2
CT2-18	75.0	2
CT2-19	75.0	2

Table A-8. Capacitor Weight/Diameter/Length

Capacitor ID #	Weight (lb)	Diameter (in)	Length (in)
CT1-1	4.1	4.0	6.0
CT1-2	4.1	4.0	6.0
CT1-3	4.1	4.0	6.0
CT1-4	4.1	4.0	6.0
CT1-5	4.1	4.0	6.0
CT1-6	4.1	4.0	6.0
CT1-7	4.1	4.0	6.0
CT1-8	4.1	4.0	6.0
CT1-9	4.1	4.0	6.0
CT1-10	4.1	4.0	6.0
CT1-11	4.1	4.0	6.0
CT1-12	4.1	4.0	6.0
CT1-13	4.1	4.0	6.0
CT2-1	4.1	4.0	6.0
CT2-2	4.1	4.0	6.0
CT2-3	4.1	4.0	6.0
CT2-4	4.1	4.0	6.0
CT2-5	4.1	4.0	6.0
CT2-6	4.1	4.0	6.0
CT2-7	4.1	4.0	6.0
CT2-8	4.1	4.0	6.0
CT2-8A	4.1	4.0	6.0
CT2-9	4.1	4.0	6.0
CT2-10	4.1	4.0	6.0
CT2-11	4.1	4.0	6.0
CT2-12	4.1	4.0	6.0
CT2-13	4.1	4.0	6.0
CT2-14	4.1	4.0	6.0
CT2-15	4.1	4.0	6.0
CT2-16	4.1	4.0	6.0
CT2-17	4.1	4.0	6.0
CT2-18	4.1	4.0	6.0
CT2-19	4.1	4.0	6.0

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